

1 **The role of plastic chemical recycling processes in a circular economy context**

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15 **ABSTRACT**

16 It is estimated that nearly 400 million tons of plastic are produced each year worldwide. However, only 10%
17 of this enormous amount is recycled after use. Currently, mechanical recycling is the dominant method, despite
18 certain operational limitations. To increase recycling rates, chemical recycling processes are emerging as viable
19 alternatives, promising the creation of more valuable products. This comprehensive review begins with an
20 introduction to ongoing plastic recycling technologies, covering general pretreatment methods for plastic waste
21 and the taxonomy of various recycling technologies and their applications for specific polymer recycling. Then
22 various aspects of chemical recycling are examined to explore its role within the context of a circular economy.
23 Detailing chemical recycling technologies, such as depolymerization pathways and thermochemical pathways, are
24 systematically elaborated. It also delves into optimization strategies, technological maturity, and economic
25 assessments of chemical recycling. In addition, this review also examines the symbiotic and/or substitutional
26 relationship between conventional recycling methods and alternatives, including biological recycling,
27 biodegradable polymers, and eco-design. Finally, the approaches to improve the large-scale application of
28 chemical recycling technology from the perspectives of technological level, infrastructure construction, public
29 awareness enhancement, and national and international policy formulation are discussed. This review aims to
30 provide theoretical support and practical recommendations for the future development of chemical recycling
31 technologies to achieve the goals of sustainable development and a circular economy.

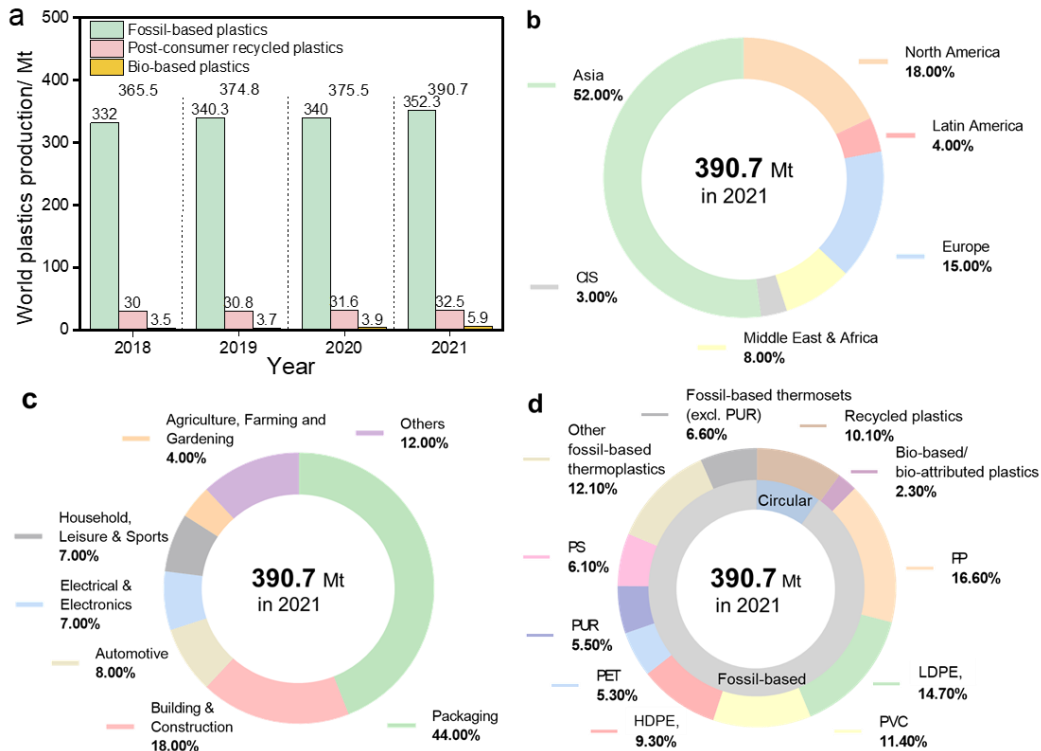
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33 **Keywords:** Plastic Waste; Chemical Recycling; Technology Readiness Level; Value Chain; Circular Economy

34 **1. Introduction**

35 Although plastics have provided functional and economic benefits to our society since the 1950s, their
36 production and use inevitably generate waste. Based on a socio-economic projection of plastic production, it is
37 expected that the total production will reach over 1,340 million metric tons (Mt) by 2050, which is almost three

38 times compared to the production volume in 2021 (390.7 Mt) [1]. In recent years, the production of plastic materials
 39 has shown a steady upward trend, despite widespread awareness of the environmental impacts of certain plastic
 40 materials beyond their intended use (**Fig. 1a**). Based on the available data, we observed that Asia accounted for
 41 more than half of the world's production in 2021(52%), with China alone contributing 32% to the world's plastic
 42 production, followed by North America and Europe, which will contribute 18% and 15% of the world's plastic
 43 production, respectively (**Fig. 1b**).

44



45

46 **Fig. 1** Global plastic production: (a) from 2018 to 2021, (b) distribution by geographic area, (c) distribution by
 47 application, and (d) distribution by polymer types, across the world in 2021 [2,3]. In Fig. 1b, CIS stands for The
 48 Commonwealth of Independent States. In Fig. 1d, PS stands for polystyrene, PUR for polyurethanes, PP for
 49 polypropylene, HDPE for high-density polyethylene, LDPE for low-density polyethylene, PVC for polyvinyl
 50 chloride, and PET for polyethylene terephthalate.

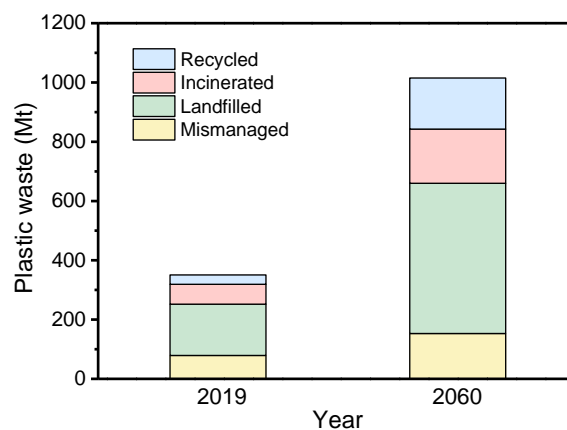
51 Over the years, the plastics market has shown steady growth, with the packaging sector leading this expansion,
 52 and accounting for almost half of the annual plastics production (with 44%, as shown by **Fig. 1c**). This growth is
 53 driven by products such as polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET), as
 54 illustrated in **Fig. 1d**. The building and construction sectors follow closely, accounting for nearly one-fifth of the
 55 market (**Fig. 1c**, data from 2021) [2,3]. Industrial sectors such as the automotive, electronic components, and
 56 electronics industries account for 15% of the global plastics market. As another major field of plastic applications,
 57 agriculture and farming activities account for 4% of the total plastic usage. Most of these plastics are used for
 58 agricultural purposes, such as greenhouse films, mulching films, and packaging for fertilizers, seeds, and
 59 pesticides. Similar to packaging plastics, plastics used in agriculture are mostly in the form of films, which are
 60 more challenging to recycle and manage compared to packaging plastics. Therefore, these agricultural plastics
 61 should also attract sufficient attention.

62 However, only 8.3% of global plastic production consists of recycled plastics, and only 1.5% comes from
63 renewable resources. In simple terms, this means that a substantial 90.2% of production still depends on virgin
64 molecules derived from fossil resources, mainly oil and natural gas (**Fig. 1d**). This evidences that the incorporation
65 of recycled plastics into industrial value chains struggles to materialize within a circularity framework [4].

66 Although it appears to be a promising endeavor, the recycling of plastic waste involves a complex array of
67 technical intricacies and nuanced considerations, ranging from logistics to health concerns. Currently, there are
68 four well-defined categories for recycling end-of-life plastic materials, known as primary and secondary recycling
69 routes (via mechanical processes), tertiary recycling (via chemical routes) and quaternary recycling (a term used
70 for direct incineration) [5]. These four routes are further presented in sections 2 and 3.

71 Nowadays, mechanical approaches remain the most widely used technologies for the large-scale treatment of
72 plastic solid waste (PSW) [6]. However, the global recycling rate remains relatively low because these recycling
73 methods are only effective for certain specific polymer materials (mainly PET and polyolefins), and often for pure,
74 unmixed streams. In fact, in the United States and Europe, the overall recycling rate for plastics from household
75 and collective uses is less than 30% [4,7].

76 As a result, the accumulation of PSW reached approximately 353 Mt in 2019. While some of this PSW is
77 mechanically recycled, the majority is either incinerated and landfilled (in certain countries) or mismanaged and
78 dumped in terrestrial and aquatic ecosystems [8,9]. This release of plastic into the environment collaterally induces
79 the formation of microplastics and nanoplastics, which raises concerns about ecotoxicity. This current end-of-life
80 of PSW is illustrated in **Fig. 2**, which was generated using data from the Organization for Economic Cooperation
81 and Development (OECD) ENV-Linkages model [10]. While the proportion of PSW subjected to incineration
82 seems to remain constant (around 18%), its mass will undergo a pronounced amplification (increasing by almost
83 67 Mt to cross the threshold of 182 Mt). Through a ripple effect, the volume of unmanaged post-consumer waste
84 is expected to increase from 79 to 153 Mt. In addition, the dominant method of controlled landfill disposal is
85 expected to continue as the predominant modality for the management and post-consumer treatment of plastics.
86 By 2060, projections suggest that the mass of PSW landfilled will increase to 507 Mt, representing more than fifty
87 percent of plastic materials facing their final fate [10]. In the current context, with absent regulatory incentives or
88 substantiation for chemical recycling techniques, the proportion of plastics earmarked for recycling - primarily of
89 a mechanical nature - will remain in a state of inertia, hovering around the 17% threshold.



91 **Fig. 2** PSW management per category (mechanical/chemical recycling, incineration, landfilling and
92 mismanagement), in million metric tons, from the OECD ENV-Linkages model. Data illustrated for 2019 and as
93 a projection for 2060.

94 Chemical recycling remains a strategic pathway for treating specific types of PSW, including composites,
95 unsorted streams, thermoset plastics, and plastics that have been exposed to certain pathogens or microorganisms,
96 in a circular system. Although some chemical approaches are still either economically unviable or not fully
97 technically feasible, according to the European Commission, adopting a circular economy model could lead to an
98 expected reduction of around 450 Mt of carbon emissions and savings of around 600 billion Euros by 2030 [10–
99 13].

100 Chemical recycling is beginning to gain traction among researchers and those interested in implementing it.
101 A wealth of comprehensive reviews of chemical recycling already exists. However, questions about its role in
102 circular economy strategies, sustainable strategies, and economic drivers still need to be explored in depth.

103 In addition to these concerns, this study addresses other important perspectives and discussions. These include
104 the potential application scenarios, the technology readiness level, and the value chains of chemical recycling
105 methods. The risk of an imbalance between plastic waste generation and chemical recycling rates, as well as the
106 relationship between waste recycling and degradable polymers are also discussed in this work. In view of the
107 escalating environmental pollution caused by plastic waste and the ongoing issue of energy shortage, accelerating
108 the development and implementation of chemical recycling is an urgent and inevitable task. It is expected that this
109 study will provide researchers, industry stakeholders, and policy-makers with a broader perspective on chemical
110 recycling in the context of a circular economy.

111 **2. Ongoing technologies for plastics recycling**

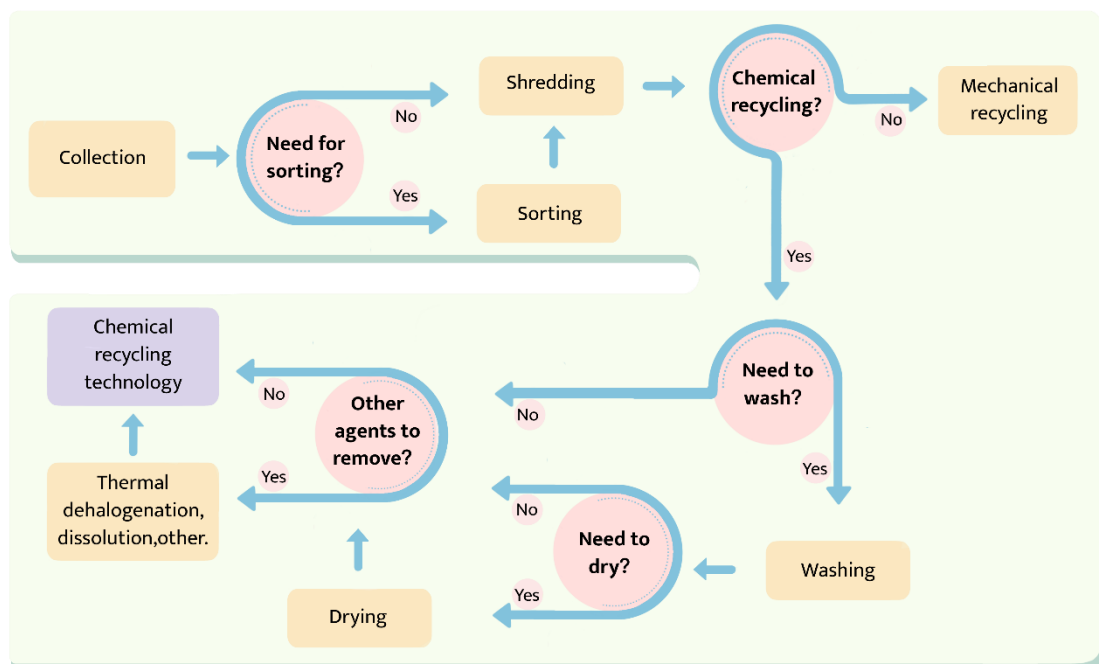
112 In the context of advancing towards a circular economy, the recycling of plastic solid waste (PSW) is pivotal.
113 Currently, a variety of methods are employed for plastic recycling, each offering distinct advantages and limitations
114 based on the type of material and its intended application. Rather than seeking a single perfect solution, a more
115 effective approach involves combining these techniques according to the specific characteristics of the waste
116 stream. This ensures efficient management of PSW and directs the resulting products into established or emerging
117 value chains, supporting a circular economy model. This section aims to outline the current landscape of recycling
118 technologies, providing a detailed classification and overview of the alternatives available. Given that conventional
119 recycling methods may not address every type of PSW effectively, it is crucial to first address fundamental steps
120 in waste management before considering chemical recycling. This comprehensive discussion includes general
121 pretreatment processes, the taxonomy of recycling technologies, and specific recycling methods for different
122 polymers.

123 **2.1 General pretreatment of plastic waste before recycling processes**

124 The critical constraint for effective recycling of post-consumer plastics is that existing recycling processes
125 typically only accommodate sorted, single-material streams, characterized by limited external contamination
126 (including pollutants and hazardous materials). This reality contrasts sharply with the situation for most plastics
127 found in households (where a proportion ends up in general waste streams, mixed with food leftovers and various

128 types of waste in many countries), as well as plastics from medical procedures and practices [5]. For example, the
 129 mechanical recycling of PSW with harmful additives, such as flame retardants (especially bromide-containing
 130 molecules), stabilizers, and plasticizers could increase environmental pollution, including water contamination
 131 [14,15]. Simultaneously, it is essential to sterilize plastic waste from the healthcare sector before subjecting it to
 132 mechanical processes. The justification for intentional incineration of these contaminated materials is firmly rooted
 133 in adherence to health-centered protocols and recommendations [16].

134 Consequently, before any recycling option, PSW is subjected to specific pre-recycling steps, the number and
 135 nature of which vary depending on the type of polymers to be recycled, the level of contamination (both in terms
 136 of type and quantity), and the intended recycling technology to be subsequently applied [17,18]. In general, these
 137 pre-recycling steps include: (i) collection; (ii) sorting of PSW based on its intrinsic characteristics; (iii) shredding;
 138 and (iv) removal of impurities (**Fig. 3**).



139

140 **Fig. 3** General steps for obtaining plastic feedstock from plastic waste for recycling technologies.

141 Both collection and sorting are the cornerstones of any recycling initiative. They play an important role in
 142 reducing the cost of recycling by segregating waste into different polymer classes, thereby enabling the targeted
 143 application of specific technologies [19]. Sorting of plastic streams can be performed either manually or by
 144 exploiting their physical and chemical properties. **Table 1** provides examples of different sorting techniques [20–
 145 23].

146 **Table 1.** Examples of common sorting techniques, according to some authors [20,21].

| Sorting type | Property exploited | Principle |
|----------------------------------|--------------------|--|
| Automated optical sorting | | It uses high-speed cameras and spectral sensors to recognize and distinguish various types of plastic waste by studying the form, color, light reflectance, and light absorption features of the material. |

| | | |
|---------------------------------|------------------|---|
| Thermal adhesion sorting | Softening point | By heating a surface, plastics soften according to their softening temperature. Consequently, some of them start adhering to the surface, allowing the segregation of divergent groups. |
| Float-Sink sorting | Specific gravity | Wastes are thrown into a solvent pool, whose specific gravity is adjusted to divide plastics into groups above or below their density. |
| Dry zig-zag sorting | Specific gravity | Plastics are placed in contact with a counter-current airflow, causing some materials to drop or rise towards corresponding exits. |
| Electrostatic sorting | Work function | Charged objects are subjected to an electric field and separated according to the magnitude of their charge. |
| Froth flotation sorting | Hydrophobicity | Similar to float-sink sorting but employing an aqueous solution of sodium sulfonate, to separate materials based on their hydrophobicity. |
| NIR sorting | NIR absorption | Wastes are subjected to near-infrared wavelengths, and specific absorptions are registered and used to discriminate between groups. |

147 Once sorted, the subsequent shredding and extrusion steps serve to increase the effectiveness of the
148 pretreatment and recycling methods by reducing the size of the material particles. This reduction improves heat
149 and mass transfers [24]. Therefore, a range of processes are used, depending on the specific component to be
150 recovered and the recycling technology selected. Several pre-treatment methods are typically required prior to
151 chemical recycling processes, including: (i) washing; (ii) thermal dehalogenation; and (iii) solvent-based
152 purification (or dissolution). Washing consists in the introduction of cold or hot water or dilute basic aqueous
153 solutions, such as NaOH, to remove salts and inorganic contaminants. However, subsequent drying is often
154 required, particularly when certain thermochemical recycling routes are employed [17]. Thermal dehalogenation
155 is used to remove halogen compounds from plastic waste, which is particularly important in the chemical recycling
156 of polyvinyl chloride (PVC). Halogens can interfere with thermochemical processes due to their corrosive nature,
157 releasing substances such as acid gases (e.g., HCl and H₂S). In addition, thermal dehalogenation assists in the
158 removal of benzene species. Typically, this process is performed at temperatures in the range of 240 to 340 °C
159 [17,24]. Higher temperatures could potentially affect the basic molecular structure of the polymer [17]. Finally,
160 solvent-based purification involves dissolving the primary polymer in the waste feedstock using a selective solvent,
161 while suspending impurities such as pigments, dyes, metals, and additives. The subsequent separation and recovery
162 of the solvent results in a waste feed with improved recyclability potential. This technique is widely used on an
163 industrial scale, particularly in the production of recycled plastic-based pellets [17,25].

164 2.2 Taxonomy of plastic recycling technologies

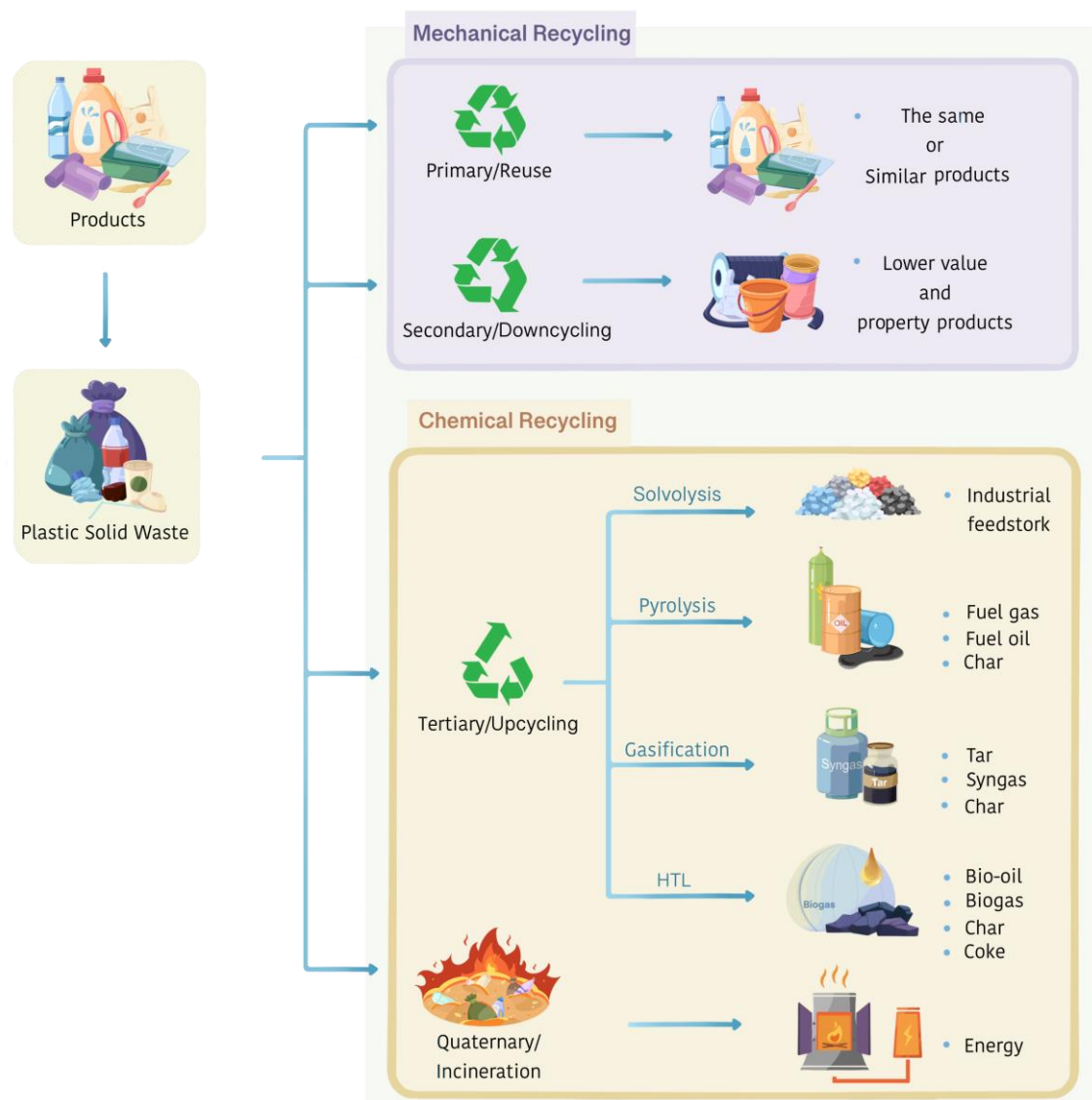
165 As noted above, plastic recycling technologies can be divided into four distinct categories, introduced primarily
166 by the American Society for Testing and Materials (ASTM) D7209 standard, namely primary, secondary, tertiary,
167 and quaternary recycling options (**Fig. 4**). Primary and secondary recycling routes refer to mechanical methods, in
168 which PSW is subjected to sorting, grinding, washing, and final extrusion to produce batches of recycled pellets.
169 The advantage of primary recycling is its high economic efficiency, but the disadvantage is the limited amount of
170 waste suitable for this approach, as most post-consumer waste does not meet the required specifications for primary
171 recycling. An illustrative example is the “bottle-to-bottle” recycling of only certain high-purity PET grades [5].

172 Secondary recycling primarily involves the mechanical transformation of plastic waste into materials other
173 than those for which the original materials were intended. This process typically results in products of lower value

174 and quality, hence it is usually called "downcycling." Although the recycling rate is not high, a significant portion
 175 of post-consumer materials undergo downcycling. For example, plastic waste from food packaging can be
 176 granulated and repurposed into non-food-grade plastic items, such as flower pots, paint buckets, shampoo bottles,
 177 and drip irrigation tape [5]. Besides, one drawback of primary and secondary recycling is that plastics can only be
 178 recycled for a limited number of cycles due to a decrease in molecular weight and resulting lower performance.

179 Conversely, the intentional breakdown of polymers into repolymerizable monomers or other lower molecular
 180 weight building blocks (for the chemical or energy sectors) under controlled conditions is referred to as "chemical
 181 recycling" or "tertiary recycling" [5,26]. These tertiary recycling techniques are often referred to as "upcycling"
 182 methods (See section 3).

183 Finally, quaternary recycling refers to incineration, where plastic waste is burned to generate heat. This heat
 184 can be captured and used to heat buildings or generate electricity. Countries such as the United States, Japan, and
 185 Singapore have adopted this approach [27,28]. However, this process raises environmental concerns, including the
 186 production of toxic gases and heavy metal-contaminated ash. The environmental and health impacts of waste
 187 incinerators are highly dependent on the emission control technology, as well as the design and operation of the
 188 incinerator [29].



190 **Fig. 4** Taxonomy of the different PSW recycling technologies.

191 **2.3 Recycling Methods for Specific Polymers**

192 As noted above, not all PSW are suitable for all recycling technologies. Plastic materials, which are
193 characterized by different molecular structures, have intrinsic properties that vary widely. These properties include
194 density, melting temperature (T_m), glass transition temperature (T_g), maximum thermal decomposition temperature
195 (T_{max}), and other mechanical properties. While these characteristics direct these polymers towards different
196 applications, they also influence the recycling strategy. To facilitate the proper assignment of each polymer
197 category to its appropriate recycling path and to improve sorting accuracy, specific codes ranging from 1 to 7 have
198 been introduced by the Society of the Plastics Industry (SPI). Pure PSW is identified by codes 1 to 6, while end-
199 of-life mixed plastics are grouped under the SPI code 7. **Table 2** (available in the supplementary material)
200 summarizes some of these properties, recycling rates and recycling methods for polymers based on their respective
201 SPI codes. A brief description of these materials, and their current recycling methods is also discussed below.

202 **2.3.1 Polyethylene terephthalate: PET (SPI code 1)**

203 PET stands as a resilient and malleable plastic material rendering it highly suitable for beverage containers,
204 fibers, and filaments. Notably, PET is the predominant polymer utilized for single-use packaging on a global scale,
205 finding application in a range of industries [30]. Given its efficient and effective collection and sorting, PET boasts
206 the highest recovery rate among polymers on a global scale [30,31]. Typically, most PET is recycled through
207 secondary recycling despite undergoing a decrease in chain lengths and ductility during its mechanical recovery.
208 Nevertheless, the resultant materials remain qualified for fibers manufacture [30,32].

209 **2.3.2 Polyolefins: HDPE, LDPE, and PP (SPI codes 2,4, and 5, respectively)**

210 As the recycling approaches are similar to each other, HDPE, LDPE, and PP are usually discussed together in
211 literature [30,33–35]. HDPE is usually used in toys, utensils, films, bottles, and pipes; LDPE for packaging for
212 computer hardware, trays and general-purpose containers, cling wrap, and grocery bags; and PP serves for reusable
213 food containers, prescription bottles, bottle caps, carpets, rugs, and mats [36,37]. Like PET, mechanical approaches,
214 are used for recycling those polyolefins. Owing to its remarkable thermal stability, as well as higher crosslinking
215 rates than PP [38], polyethylene can survive melting and remolding cycles multiple times during mechanical
216 recycling processes. For example, LDPE can be extruded up to 40 times at a temperature of 240 °C [30]. Due to
217 the C–H groups at tertiary carbon centers in polypropylene being more susceptible to oxidation during reprocessing,
218 the mechanical properties of polypropylene deteriorate more rapidly when recycled through mechanical means
219 than those of polyethylene. When considering applying tertiary recycling to those polyolefins, pyrolysis appears
220 as the most efficient, although the thermal cracking is more difficult in HDPE than in LDPE and PP [39].

221 **2.3.3 Polyvinyl chloride: PVC (SPI code 3)**

222 PVC is an exceedingly versatile polymer, capable of giving rise to an array of products with varying lifespans,
223 spanning from long-term applications such as water pipes and medical equipment to short-term items like
224 raincoats, tablecloths, and shower curtains. Challengingly, in the realm of processed PVC blends, an array of
225 functional additives is employed, enhancing the properties of PVC products or rendering them more amenable to

226 processing. These additives include thermal stabilizers, lubricants, flow modifiers, agents for enhancing
227 mechanical properties, plasticizers and, typically, a substantial quantity of mineral fillers, such as chalk, talc, and
228 titanium white [40,41]. However, those additives in PVC-based materials can be leached during the recycling
229 process, but also compromise the quality of the recycled products.

230 As PVC waste remains one of the most challenging materials to recycle, it has for a long time been incinerated.
231 However, direct incineration leads to the emission of toxic gases (SO₂, NO_x), heavy metals, and solid particles
232 through the flue gas. It also contributes to the formation of hazardous compounds like polychlorinated
233 dibenzodioxins and other chlorinated organic compounds [42]. Currently, secondary recycling of PVC is mastered,
234 although the intricate blend of additives found in PVC waste implies case-by-case adjustments, which make
235 secondary recycling more expensive than for PET or polyolefins [43,44]. Pyrolysis of PVC has been investigated,
236 even if it induces HCl emission and subsequent eventual equipment depreciation. A mechanochemical strategy
237 can be used to grind PVC with a HCl scavenger, such as CaO. This approach yields a calcium salt by-product that
238 can be readily removed through washing [45]. Another innovative method involves co-pyrolysis of PVC with
239 cellulose, effectively adsorbing HCl and concurrently reforming cellulose pyrolysate [46]. In essence, advancing
240 more efficient techniques, catalysts, and HCl inhibitors remains imperative to effectively recycle PVC waste
241 through chemical procedures [30].

242 **2.3.4 Polystyrene: PS (SPI code 6)**

243 PS is a highly versatile and chemically stable polymer, making it a popular choice from appliances and
244 automotive parts to electronics, food services and packaging. PS is used in both solid and expanded forms. General-
245 purpose PS is transparent, rigid, and rather brittle. While expanded polystyrene (EPS) foam, often called PS foam
246 or styrofoam, is frequently used for insulation and packaging purposes. A unique practical barrier for PS recycling
247 compared to other plastic recycling is that much of the PS waste is in the form of EPS foam, which has a high
248 volume-to-mass ratio, thus making it more expensive to transport to a central recycling facility [37].

249 Besides employing dissolution techniques (which is not included in this review), PS can be broken down by
250 pyrolysis in the presence of a magnesium-impregnated solid catalyst, resulting in a mixture of hydrocarbons such
251 as benzene, toluene, ethylbenzene, styrene, and α -methylstyrene [47]. The maximum temperature of which process
252 is approximately 550 °C [48]. Research into the breakdown of PS in supercritical solvents (benzene, toluene,
253 ethylbenzene) at 310-370 °C revealed that toluene was more successful than the others in recovering styrene from
254 PS [49].








255 **2.3.5 Miscellaneous (SPI code 7)**

256 SPI code 7 encompasses a diverse array of thermoplastics and thermosets, distinct from those categorized under
257 SPI codes 1 to 6. It also includes biodegradable plastics. Among these thermoplastics and thermosets, notable
258 mentions are polycarbonate (PC), polyamides (PA), acrylonitrile butadiene styrene (ABS), polymethyl
259 methacrylate (PMMA), polyethersulfone (PES), polytetrafluoroethylene (PTFE), polyurethanes (PUR), and
260 epoxies, among others.1

261 While certain polymers from this category can be mechanically recycled, they often partially lose some of their
262 physical properties. Investigations have delved into the pyrolysis of various of these “SPI 7” polymers, including
263 PC, PTFE, PA, PMMA, and even PUR and epoxy composites [11,26,50–55]. Unlike PE and PP which fragmentize

264 randomly, PTFE, PA and PMMA can be pyrolyzed into products primarily composed of their respective monomers
265 [11]. For instance, pyrolysis of PMMA yields an impressive monomer content of nearly 98% [50]. PET, PC, and
266 PUR are all amenable to depolymerization through solvolysis. However, solvolysis yields a mixture of final
267 products (either high molecular-weight oligomeric polyols or aromatic N-containing oligomers) posing challenges
268 in terms of separation and purification [26,56].
269

270 **Table 2. SPI codes, recycling rates, recycling methods for different types of plastic solid waste**

| SPI code | Chemical name (Abbreviations) | SPI Identification | Properties [5,25,57–59] | | | | | | Recycling rate from containers & packaging (%) [7] | Total recycling rate in MSW (%) [7] | Current main recycling methods |
|----------|----------------------------------|---|-------------------------------|---------------------|------------------------|-----------------------|------------------------|-----------|--|-------------------------------------|---|
| | | | Density (g·cm ⁻³) | T _m (°C) | T _g (°C) | T _{max} (°C) | σ _{max} (MPa) | E (GPa) | | | |
| 1 | Polyethylene terephthalate (PET) |  | 1.33-1.45 | 280-320 | 70-85 | 435 | 47 | 3.1 | 25.4 | 18.5 | Mechanical recycling, pyrolysis, solvolysis (glycolysis, aminolysis, alcoholysis, hydrolysis) [25,30,60–62] |
| 2 | High-density polyethylene (HDPE) |  | 0.94-0.96 | 200-300 | -130 - -100 | 460 | 18-35 | 0.07-1.40 | 14.8 | 8.9 | Mechanical recycling, pyrolysis [39] |
| 3 | Polyvinyl chloride (PVC) |  | 1.38-1.55 | 180-210 | 80-90 | 290, 465** | 50-75 | 1.0-3.5 | Neg. | Neg. | Mechanical recycling, pyrolysis [5,45,46] |
| 4 | Low-density Polyethylene (LDPE) |  | 0.91-0.93 | 160-260 | -130 - -100, -30 - -10 | 460 | 8-23 | 0.2-0.5 | 9.9 | 4.3 | Mechanical recycling, pyrolysis [39] |
| 5 | Polypropylene (PP) |  | 0.90-0.91 | 230-270 | -20 - 20 | 470 (in air) | 21-37 | 1.1-1.3 | 2.7 | 0.6 | Mechanical recycling, pyrolysis [39] |
| 6 | Polystyrene (PS) |  | 1.05 | 180-280 | 80-105 | 435 | 45-65 | 3.2-3.25 | 3.6 | 0.9 | Dissolution, pyrolysis, and solvolysis [47,49,63,64] |
| 7 | Others* |  | varies | varies | varies | varies | varies | varies | Neg. | 26.7 | Mechanically recycling for PC, PES and epoxy [32,65,66], pyrolysis for PC, PTFE, PA, PMMA, PUR and epoxy composites [11,26,50–55] solvolysis (alcoholysis, glycolysis, hydrolysis, and aminolysis) for PC and PUR [26,56,67,68] |

271 Neg.= Negligible, less than 0.02%.

272 * Including polylactic acid, acrylonitrile butadiene styrene, nylon and polycarbonate.

273 ** There are two separate degradation regimes and relative two maximum mass loss temperature for PVC.

274 T_m: Melting temperatures.

275 T_g: Glass transition temperature.

276 T_{max}: Temperatures at which mass loss rate is the highest (T_{max}) obtained from TGA results rounded to nearest 5 °C and measured at 10 °C·min⁻¹ in N₂ unless stated.

277 σ_{max}: Maximum tensile strength.

278 E (GPa): Tensile modulus.

279 **3. Chemical recycling: a valuable tool for a circular economy**

280 As stated before, applying mechanical recycling does not allow to completely valorize plastic solid waste
 281 (PSW) as materials downgrade towards applications with lesser economical value. Even though it enables the
 282 reincorporation of these materials towards the existing economy, it does not take advantage of the entire value of
 283 these waste streams. Therefore, chemical recycling emerges as a critical alternative in the pursuit of a circular
 284 economy, addressing the limitations of traditional methods.

285 In this section, we will explore the role of chemical recycling as an essential component of circularity. We
 286 begin by defining chemical recycling and examining the various technologies available, along with potential
 287 optimization strategies. Despite varying levels of technological maturity, we will evaluate the current status and
 288 future prospects of these technologies to underscore their significance. We will then present different pathways for
 289 treating PSW, including both homogeneous and mixed streams, and outline the potential value chains for recycled
 290 products, acknowledging that not all PSW are equally valorized. Finally, we will provide an economic assessment
 291 to identify areas for improvement in chemical recycling options, as well as to assess their socioeconomic and
 292 environmental impacts.

293 **3.1 Chemical recycling technologies**

294 From a molecular perspective, chemical recycling involves advanced processes that convert PSW into smaller
 295 molecules - either liquid or gaseous - that can then be reused as fuels, reagents, or as building blocks for the
 296 production of new plastics. The term "chemical" entails an inherent change in the structural composition and
 297 cleavage of the major chemical bonds in the polymer structure. It is important to note that not all plastics are
 298 created equal, and different plastics undergo distinct chemical recycling processes. Polyesters (such as PET and
 299 PLA), polyamides (such as nylon 6), polycarbonate, and polyurethanes can be effectively recycled through
 300 solvolysis processes. In contrast, polyolefins (such as LDPE, HDPE, and PP) are primarily suited for pyrolysis.

301 Chemical recycling can be broadly categorized based on the operating temperature and the nature of the bond
 302 cleavage: either controlled depolymerization at temperatures around 300-350 °C or molecular disintegration
 303 through pyrolysis at temperatures exceeding 400 °C [24]. Controlled depolymerization involves precise cleavage
 304 of specific covalent bonds, whereas pyrolysis entails a more random destruction of the polymer structure. **Table 3**
 305 highlights the main reactions observed in chemical recycling of several different polymers treated at either a low
 306 (solvolysis) or a high temperature (pyrolysis), and provides examples of commonly recovered low-molecular-
 307 weight compounds.

308 **Table 3.** Illustration of the key reactions involved in chemical recycling.

| | Reactions | Equations | Ref. |
|---------|------------------------------------|-----------|------|
| Solvoly | 1 Reductive depolymerization | | [69] |

| | | | |
|----|--|--|------|
| 2 | Hydrolysis Pathway A: acid neutral Pathway B: alkaline | | [70] |
| 3 | Methanolysis | | [71] |
| 4 | Glycolysis | | [72] |
| 5 | Aminolysis | | [73] |
| 6 | Cracking | | [24] |
| 7 | β -scission | | [24] |
| 8 | Hydrogen transfer | | [24] |
| 9 | Propagation | | [24] |
| 10 | Disproportionation | | [24] |
| 11 | Coupling | | [24] |

Pyrolysis

309 Notes: PCL: polycaprolactone; TPA: terephthalic acid; EG: ethylene glycol; BPA: bisphenol A; DMC: dimethyl carbonate;
 310 BHETA: bis(2-hydroxyethylene)terephthalamide.

311 In the following sections, we will delve into these two distinct pathways of chemical recycling: depolymerization
 312 processes operating under mild conditions and thermochemical pathways characterized by high-temperature
 313 treatments. Each pathway offers unique advantages and challenges, which will be explored in detail.

314 3.1.1 Depolymerization pathways (low temperatures)

315 Depending on the operating temperature, which influences the way chemical bonds within the polymer are
 316 broken, chemical recycling can be categorized into controlled depolymerization (under mild conditions) or
 317 molecular disintegration (under more intense thermochemical treatment conditions). These two pathways are
 318 described separately below.

319 The term "depolymerization" refers to the methodical breakdown of a polymer into its constituent monomeric
 320 units. This includes techniques such as reductive depolymerization and solvolysis [30]. Reductive
 321 depolymerization is a reaction that converts a polymer into high-value compounds, such as polyols or polyamines,
 322 through the action of a transition metal catalyst and a reducing agent (H_2 or silanes). Reductive depolymerization
 323 is usually carried out at relatively low temperatures, ranging from 65 to 160 °C [74]. Fernandes demonstrated that

324 it was possible to convert polycaprolactone (PCL) to hexan-1,6-diol using zinc acetate dihydrate ($\text{Zn}(\text{OAc})_2 \cdot 2\text{H}_2\text{O}$)
325 and phenylsilane (PhSiH_3) as the catalyst and reducing agent, respectively (**Table 3**, line 1) [69]. Similarly, in
326 solvolysis reactions, the solvent cleaves the bonds between the monomers, with or without an additional catalyst.
327 Depending on the solvent used, different categories are distinguished, each with different resulting end products:
328 hydrolysis takes place in the presence of water, while alcoholysis employs an alcohol, often an aliphatic one.
329 Glycolysis profits from the utilization of glycols, whereas aminolysis is conducted by the action of aliphatic or
330 aromatic amines.

331 Hydrolysis has proven to be efficient for the chemical recycling of polymers containing *O*- and/or *N*-containing
332 (co)-monomers, such as polyesters, polyurethanes (PURs), polyamides, or phenolic resins. This results in the
333 formation of polyols, amines, or other intermediates or monomers, depending on the nature of the polymer being
334 treated. Hydrolysis can be carried out under neutral, alkaline, or acidic conditions using hydroxides or sulfuric acid
335 [75]. The most common example is the hydrolysis of PET at temperatures between 150 °C and 300 °C and at
336 pressures between 1 and 4 MPa, yielding predominantly terephthalic acid (TPA) and ethylene glycol (EG) (**Table**
337 **3**, line 2) [70].

338 Alcoholysis involves the depolymerization of polymers in an alcohol-based medium, sometimes in the
339 presence of an acid or a base catalyst. The most notable approach is methanolysis using methanol. Chiu and
340 coworkers reported optimal methanolysis of polycarbonate in less than 5 min under batch conditions at 240 °C,
341 producing both bisphenol A (BPA) and dimethyl carbonate (DMC) (**Table 3**, line 3) [71]. Glycolysis relies on the
342 use of glycols with or without the addition of a catalyst (organometallic, amine, or acid-base catalysts) [72].
343 Ethylene glycol (EG) is the most commonly used solvent for glycolysis and has been found to be effective for the
344 chemical recycling of PUR foams (**Table 3**, line 4) [72]. Finally, aminolysis uses a solvent with an aliphatic or
345 aromatic amine function, such as ethanolamine, in the presence of a catalyst such as sodium acetate or glacial
346 acetic acid. Shukla *et al.* [73] reported the depolymerization of PET to bis(2-hydroxyethylene) terephthalamide
347 (BHETA) with a 91% yield in the presence of ethanolamine and sodium acetate as an aminolytic agent and catalyst,
348 respectively (**Table 3**, line 5).

349 **3.1.2 Thermochemical pathways (high temperatures)**

350 Depending on the conditions used, thermochemical processes can be categorized as pyrolysis (in an oxygen-
351 deficient atmosphere), gasification (in an oxygen-rich atmosphere) or hydrothermal liquefaction (HTL) using
352 supercritical water (sc. H_2O), as illustrated in **Table 4**.

353 During pyrolysis, the hydrocarbon chains that make up the polymers are broken down into simpler, low-
354 molecular-weight units. This process generally results in the production of: (i) a gas phase, containing volatile
355 compounds; (ii) a pyrolysis oil that integrates a range of hydrocarbons, aromatics, and other liquid organic
356 compounds; and (iii) a carbonaceous residue called biochar. The relative proportions of these different fractions
357 depend on the reaction conditions applied [18,76]. Pyrolysis is typically applied to PSW at temperatures in the
358 range of 400 °C to 700 °C and under an inert atmosphere [76,77]. The minimal temperature required depends on
359 the material being treated. Polymers with high melting points typically require temperatures higher than 500 °C
360 [18]. Pyrolysis has been shown to be efficient for a wide range of plastics (PET, polyolefins, PVC, PURs, etc.),
361 but also for multilayer, multi-material, coated plastics, mixed plastic waste (MPW) and composites, eliminating,
362 to a certain extent, the need for sorting [78]. Common reactors used for PSW pyrolysis include pressure vessels,
363 tubular reactors, fixed bed reactors, and fluidized bed reactors [77]. During pyrolysis, the degradation of polymers

364 is caused by cracking and radical chain reactions. Random cleavage of molecules produces smaller alkanes,
 365 alkenes, and radical chains that further react via: (i) cracking; (ii) β -scission; (iii) hydrogen transfer; (iv)
 366 propagation; (v) disproportionation; and (vi) coupling reactions (**Table 3**, lines 6 to 11) [24,79]. In general, as
 367 temperature increases, gas yield increases at the expense of liquid yield by accelerating reaction kinetics [18,77].
 368 Because pyrolysis is energy-intensive, catalysts are often used to reduce the activation energy required for polymer
 369 decomposition [17,24,76,77]. These catalysts can also be used to effectively remove impurities or limit the
 370 formation of hazardous materials (e.g. chloride compounds in the case of PVC pyrolysis). Commonly used
 371 catalysts include zeolites, acidic solids, heavy metal salts, and noble metal-based catalysts [17,76]. However, the
 372 recovery of these catalysts is not always efficient, which increases operating costs. In addition, during in-situ
 373 catalytic pyrolysis, i.e., when there is direct contact between the catalyst and the plastic matrix, material deposition
 374 can rapidly deactivate the catalytic sites [17,77]. An alternative approach is ex-situ catalytic pyrolysis, which
 375 involves a two-step process. This configuration has the advantage of reducing the risk of catalyst poisoning, as a
 376 second catalytic stage would process the intermediate volatiles from the first reactor, facilitating their recovery and
 377 reuse [24]. It should also be noted that current research is also dedicated to the possibility of pyrolyzing unsorted
 378 PSW to yield certain intermediate molecules that could enable the creation of novel solvents or liquid fuels for
 379 transportation purposes.

380 In hydrothermal liquefaction (HTL), supercritical water acts as both the solvent and catalyst. Its advantages
 381 include inhibiting undesired side reactions, improving product selectivity, removing impurities such as halogens,
 382 nitrogen, and oxygen compounds, and reducing coke/char formation. The main reactions involved are similar to
 383 those in pyrolysis, particularly cracking and β -scission reactions (**Table 3**, lines 6 and 7) [24]. HTL offers
 384 significant results for a wide range of PSW at temperatures ranging from 350 °C to 500 °C. However, due to the
 385 corrosive nature of supercritical H₂O and the substances dragged into the gas phase under acidic conditions,
 386 stronger steel alloys are required for this process, which may increase capital expenditures [17,24].

387 Finally, gasification is the third thermochemical route that is efficient for recovering PSW. Operating at
 388 temperatures between 700 °C and 1000 °C, gasification aims to produce a synthetic gas, or syngas, containing
 389 mainly CO and H₂. Unlike pyrolysis, gasification uses an oxidant such as air, pure oxygen, steam, or sc.H₂O. Steam
 390 gasification is reported to produce a syngas with a higher heating value than air gasification due to the absence of
 391 nitrogen, resulting in hydrogen enrichment [18,76,77]. Gasification has been shown to be efficient in converting a
 392 wide range of polymers to syngas, which can subsequently be upgraded to hydrocarbon-based monomers or fuels
 393 through a Fischer-Tropsch process.

394 **Table 4.** Summary of the main characteristic for thermochemical recycling technologies.

| Technology | Temperature range (°C) | Type of products produced | Main advantages | Particular requirements | |
|----------------------------------|------------------------|--|---|--|--|
| Pyrolysis | 400 ~ 700 | Low weight mixture of hydrocarbons and char. | molecular products, of composites and/or multi-material plastics. | It offers the versatility of treating mixed plastic strains, and/or | It demands the use and management of catalysts and various reactor configurations, increasing operational costs. |
| Hydrothermal liquefaction | 350 ~ 500 | Low weight mixture of hydrocarbons and char. | molecular products, and Mild reaction conditions. | Inhibition of side reactions, increase in selectivity and reduction of char. | It requires reactors made of corrosion-resistant alloys, increasing capital costs. |

| | | | | |
|---------------------|------------|--|--|---|
| Gasification | 700 ~ 1000 | Syngas (mainly H ₂ and CO). | A wide range of polymers can be treated. | Higher temperatures are needed. The use of steam is intended for hydrogen enrichment. |
|---------------------|------------|--|--|---|

395 3.2 Chemical recycling strategies for mixed wastes, composites and thermosetting wastes

396 The recycling strategy for MPW and composites may differ slightly from that of homogeneous waste streams
 397 or functional groups that do not necessarily interfere with product quality or specific applications, especially when
 398 conventional recycling techniques are used. Contamination from external substances in one type of plastic can
 399 compromise the mechanical recycling of another type. For example, chlorine from PVC can pollute a polyolefin
 400 recycling stream. However, submitting a mixed stream of PSW, containing both types of materials, to pyrolysis
 401 does not undermine the production of pyrolysis oil. In this case, pyrolysis oil can still be produced from the blended
 402 feed, but careful attention must be paid to controlling the presence of chlorine in the final product [78]. To properly
 403 regulate the resulting liquid yield and quality, reaction parameters play a significant role. Different conditions can
 404 not only alter the proportion of the resulting products but also affect the distribution of functional groups or
 405 elements between different phases. Key parameters include the nature and ratio of the polymers, temperature,
 406 heating rate, residence time, catalyst type, and reactor configuration [78,80–82].

407 On the other hand, recycling composites is more challenging, especially when thermoset plastics are used as
 408 the matrix material. This is the case with some fiber-reinforced polymers (FRP). For example, the imminent
 409 retirement of first-generation aircraft and wind turbines made with carbon fiber-reinforced polymer (CFRP)
 410 composites over the next decade, coupled with the anticipated global CFRP waste reaching 20,000 tons by 2025,
 411 underscores the critical need for sustainable recycling strategies. Common methods for managing FRP include
 412 incineration (utilizing the associated heat), mechanical recycling, and landfill disposal. Although pyrolysis can
 413 recover some thermally stable fibers from these composites, it also produces pyrolysis products that can affect the
 414 properties of the recovered fibers due to thermal degradation. A similar issue occurs during mechanical recycling,
 415 where the resulting products are downgraded. Recent advancements in recycling technology offer novel
 416 approaches that promise to enhance the viability of recycling thermoset composites. Liu *et al.* [83] demonstrated
 417 a method for effectively recovering long carbon fibers and epoxy resin from CFRPs using deep eutectic solvents
 418 (DESs) and metal salt catalysts (e.g., ZnCl₂), achieving complete decomposition of the epoxy resin in hydrophobic
 419 DESs at 180°C for 1.5 h, while the recovered carbon fibers retained 94.5% of their original strength. Furthermore,
 420 Hao *et al.* [84] present an eco-friendly method for upcycling carbon fiber-reinforced polymer (CFRP) waste by
 421 decomposing the epoxy matrix under mild conditions, converting the decomposed polymer into recyclable
 422 vitrimers, and creating new hydrothermally recyclable composites with recovered carbon fibers. It is essential to
 423 integrate these new recycling technologies into the automotive, wind energy, and aerospace industries to meet the
 424 circular economy objectives.

425 Unlike thermoplastics, which are often designed for single use and require sorting before chemical recycling,
 426 certain thermosetting wastes (like tires, wind turbine blades, etc.) are bulk and easily separable from other plastic
 427 wastes. However, thermosets are covalently cross-linked polymers with exceptional mechanical strength, thermal
 428 properties, and chemical stability, making them highly desirable in structural and protective applications but
 429 particularly difficult to recycle. Mechanical reprocessing is not feasible for thermosets due to their cross-linked
 430 structure that prevents them from flowing. Chemical recycling technologies convert thermoplastics into their
 431 monomers or low molecular weight compounds, thereby enabling their reuse and becoming a crucial approach to

432 addressing this challenge. Pyrolysis has been explored for the recycling of thermoset resins [54,55]. Despite the
433 incorporation of acidic and metal catalysts, these processes are energy-intensive and produce unfavorable mixtures
434 that require purification before use [26]. Milder chemical methods have been developed to exclusively on the
435 hydrolysis of polymers carrying acid- or base-labile functional groups, such as polyurethane [85]. For epoxy resins,
436 a recent study reported a light-driven, proton-coupled electron transfer-based method for completely
437 depolymerizing insoluble thiol epoxies with varying cross-link densities and material properties [86]. This yielded
438 a well-defined mixture of monomer derivatives with a combined yield of up to 88%, which can be converted back
439 to the original bisphenol A monomer through a straightforward in situ dealkylation reaction. Furthermore, the
440 development of new thermosets has resulted in enhanced degradability by integrating stimuli-triggered cleavable
441 functional groups or dynamic covalent bonds into the network [87]. These advancements not only address the
442 recycling challenges of existing thermoset composites but also provide a foundation for designing the next
443 generation of composites that are inherently recyclable.

444 **3.3 Optimization strategies for chemical recycling**

445 Optimization of chemical recycling technologies can be based on several approaches, including improving
446 recycling efficiency, adjusting the desired products, and purifying them.

447 The continuous processing approach can improve the efficiency of chemical recycling by reducing cycle times,
448 increasing throughput, and providing better control over reaction conditions, as illustrated in **Fig. 5a** [23].
449 Continuous processes can integrate multiple steps into one system, resulting in increased efficiency and cost-
450 effectiveness.

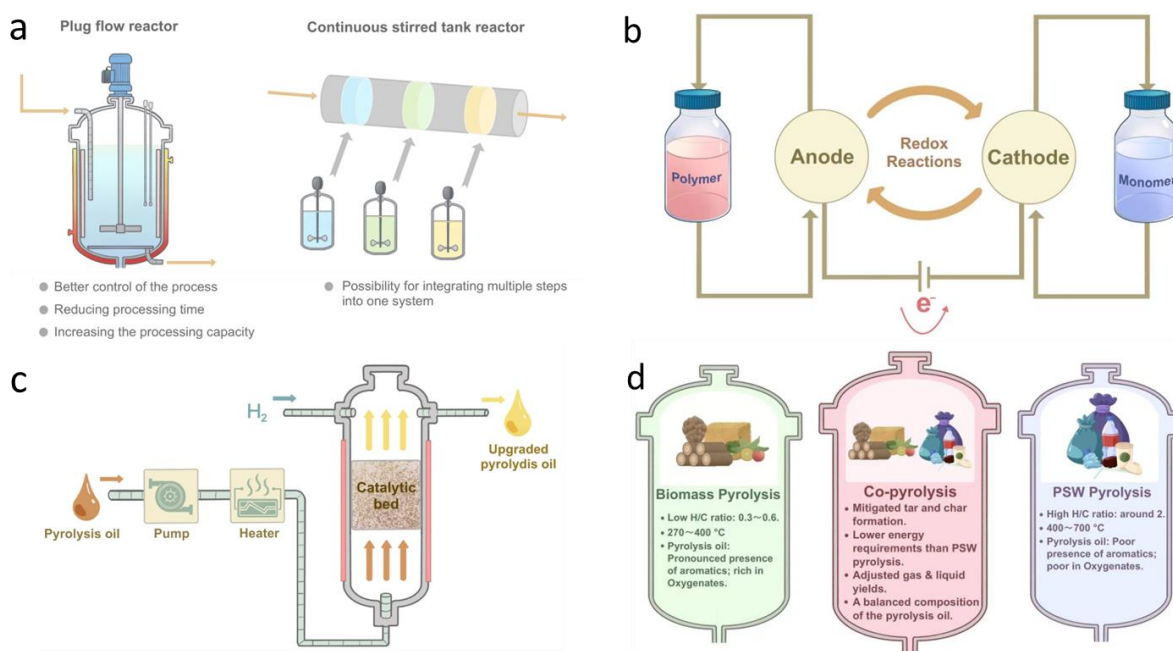
451 Electrochemical methods are also being explored as an alternative to improve recycling efficiency (**Fig. 5b**).
452 These methods use electrocatalysis and electrical energy to break down polymers into valuable chemicals or
453 monomers [88]. They offer potential advantages such as mild reaction conditions, high selectivity, and the ability
454 to target specific polymers.

455 Catalytic hydrotreating uses a hydrogen atmosphere to remove heteroatoms (N, S, O, Cl) and metals, and to
456 reduce unsaturation and aromatics in the pyrolysis oil, resulting in a narrower product distribution. This process
457 can convert polyolefins into synthetic biofuels and recover recycled monomers from various plastics such as PET,
458 PC, PS, PPO, poly(p-phenylene oxide) (PPO), and polylactic acid (PLA). However, catalytic hydrotreating
459 requires high hydrogen pressures, which may limit its application on an industrial scale. Fixed-bed (**Fig. 5c**) and
460 fluidized-bed reactors stand out as the most common configurations [76].

461 Co-pyrolysis involves the simultaneous thermal decomposition of both plastic waste and biomass, using the
462 synergy to improve the properties of the resulting output, as illustrated in **Fig. 5d**. It can serve several purposes,
463 such as mitigating tar and/or char formation, adjusting gas or liquid yields, or influencing the production of a
464 specific output [28,39]. This technology offers several advantages, including the potential use of existing
465 technological infrastructure, although a fixed bed reactor is preferred. In addition, the energy requirements are
466 lower compared to those of plastic waste pyrolysis alone, as biomass degradation occurs at lower temperatures.
467 The outcome of the process is influenced not only by the compatibility between biomass and plastic, but also by
468 the ratio of biomass to plastic, an area that is currently the focus of ongoing research. Similarly, co-gasification of
469 plastic waste and biomass has been explored to reduce tar formation during the process [77].

470 Finally, distillation and fractionation, which are commonly used as the first steps in improving the purification
471 of pyrolysis oil, provide an option for managing the wide range of products inherent in the pyrolysis of PSW. In

472 fact, distillation can efficiently separate adducts according to their respective boiling points while providing a
473 means to remove residual contaminants, such as metals [17,24].



474
475 **Fig. 5** Optimization strategies for chemical recycling: (a) Continuous processing mode, (b) Electrochemical
476 depolymerization, (c) Catalytic hydrotreatment, and (d) Co-pyrolysis with biomass.

477 3.4 Technological maturity of chemical recycling technologies

478 The aforementioned chemical recycling alternatives have different technological maturity. Some are already
479 operational at industrial scale, while others are still on development, either in academic research laboratories or in
480 the private sector. Among these technologies, pyrolysis holds significant sway due to its well-established maturity
481 in the oil and gas sector [24,25,69,70]. In fact, prominent companies active in the food packaging sector are playing
482 a pivotal role in driving the advancement of these technologies [24]. They have also been prompted by waste
483 regulations worldwide, such as the European Waste Framework Directives and the United States Environmental
484 Protection Agency's National Framework for Advance Recycling [7,89]. In addition, the incorporation of recycled
485 feedstocks, such as monomers and upgraded pyrolysis oil, helps reduce the amount of fossil-based feedstocks
486 required for their processes, thereby meeting the European Union (EU) regulation of 30% recycled plastic content
487 in new polymer items [89].

488 To date, the emergence of new chemical recycling facilities has mostly been driven by the creation of joint
489 ventures or supply agreements between large companies and growing start-ups or small businesses, leveraging
490 their complementary technical expertise. This collaborative support has enabled smaller actors to secure the
491 necessary investment for advancing their processes and ensuring economic viability. Over time, there has been a
492 growing trend for established companies to license their technologies, leading to an increase in the number of
493 recycling facilities expected to come online in the coming years [60,90].

494 Pyrolysis stands out as the most mature recycling technology due to its adaptability in managing mixed plastic
495 waste and the existing infrastructure and expertise. Key industry players in this area include well-known companies
496 such as Quantafuel, BASF, Neste, Plastic Energy, Shell and Sabic (refer to **Table S1** in the supplementary
497 material). The pyrolysis oil is used to produce valuable chemicals, fuels, and/or new plastics, while the char-like

498 granules are used as raw materials for the construction and automotive industries. The gases produced during
499 pyrolysis are often used to generate heat and electricity, a practice that reportedly offsets the energy requirements
500 of the process [17,90,91].

501 While many operators focus on recycling mixed plastic waste to add value to non-mechanically recyclable
502 materials, some have highlighted the challenge of ensuring consistent properties in the end products due to the
503 diverse nature of feedstock batches. This is particularly relevant when aiming to produce high-value items from
504 the pyrolysis oil. To address this issue, many companies have adopted a mass balance approach. This involves
505 using the resulting oil to reduce their reliance on fossil-based crude oil consumption, providing them with a wider
506 range of operational flexibility [60].

507 On the other hand, depolymerization routes are gaining momentum on an industrial scale, with notable players
508 such as Revalyu. Revalyu operates a recycling facility in Nashik, India, where they produce recycled polyester
509 yarns from PET waste [25,60]. This dynamic shift toward controlled depolymerization has also attracted the
510 attention of other industry leaders. Companies such as Aquafil, Ioniqa, and Eastman Chemical have successfully
511 validated their technologies up to technology readiness level 7, with validation and construction projects underway
512 for full industrialization soon (refer to **Table S2** in the supplementary material). Among the various solvolysis
513 pathways, glycolysis takes the lead due to its versatility and favorable operating cost profile [25,60].

514 Conversely, gasification and hydrothermal liquefaction (HTL) represent a limited number of systems that have
515 successfully demonstrated their capabilities at the industrial level (listed in **Table S3** in the supplementary
516 material). Prominent players in this field include Klean Industries, Mura Technologies, and Renasci, each with
517 established plants, while other projects are actively pursuing qualification. Notably, the growing interest in
518 sustainable aviation fuels (SAF) and green plastics, coupled with the need to diversify supply chains, is acting as
519 a catalyst to accelerate the development of these technologies [92,93].

520 **3.5 Typical value chains of chemical recycling**

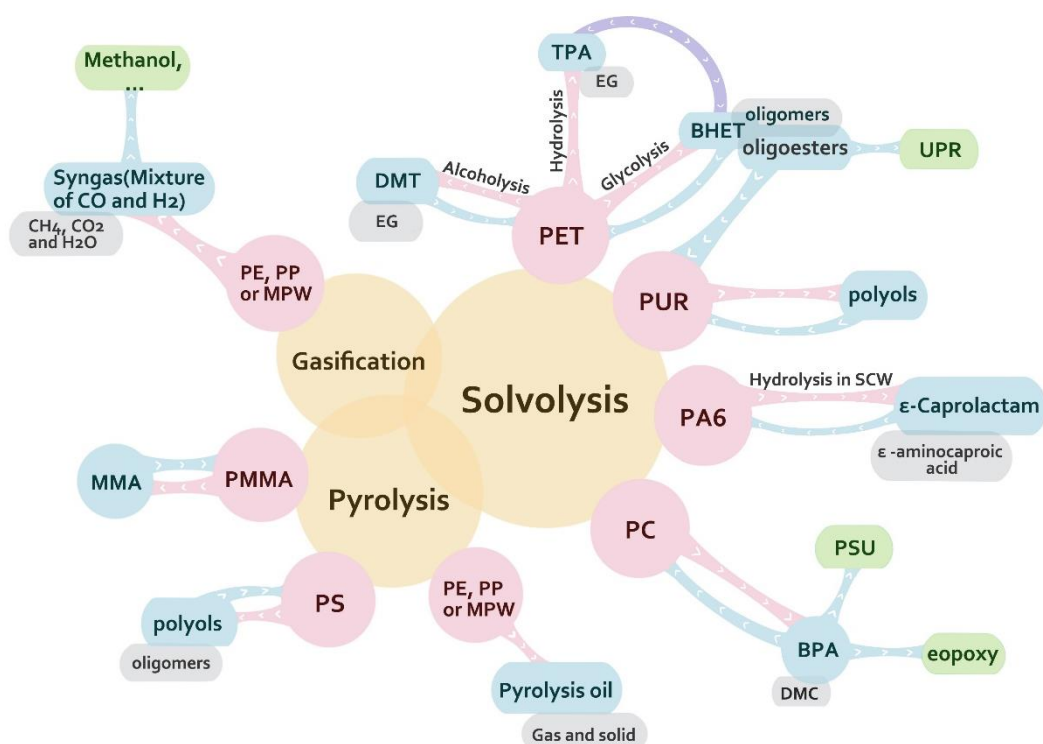
521 In scenarios where mechanical recycling of plastic waste might be cost-prohibitive or unviable, chemical
522 recycling emerges as a solution that rejuvenates plastic waste and positions it at the beginning of new value chains
523 [94]. **Fig. 6** shows a diagram delineating the value chains associated with the main chemical recycling methods:
524 solvolysis, pyrolysis, and gasification. This diagram highlights the resulting value-added products and their
525 multiple applications, including the recovery of the original polymers or the synthesis of alternative chemicals.

526 Nowadays, pyrolysis is emerging as an important method for converting plastic waste into either fuels or
527 valuable chemicals. For example, pyrolysis can be used to recover the monomers of polystyrene (PS) and
528 poly(methyl methacrylate) (PMMA), namely styrene and methyl methacrylate (MMA), which can then be reused
529 in the synthesis of the original polymers. In contrast, PE and PP tend to undergo random fragmentation, resulting
530 in a wide and skewed distribution of products, constituting the pyrolysis oil [11].

531 Compared to pyrolysis, solvolysis offers a more precise approach to the recovery of polyesters and polyamides.
532 Solvolysis processes are highly effective in treating polymers containing ester, ether, and acid amide bonds, such
533 as PET, PU, PC, and nylon, among others. PET, for example, can be subjected to alcoholysis, glycolysis, and
534 hydrolysis to break it down into its constituent monomers - dimethyl terephthalate (DMT), bis(2-hydroxyethyl)
535 terephthalate (BHET), and TPA, respectively. Repolymerization of PET can be achieved using BHET and DMT
536 without conversion, although TPA must first be converted to BHET. It should be noted that hydrolysis processes
537 are preferred over alcoholysis processes [25]. It is important to note that the products derived from the glycolysis

538 of PET are of particular value because they contain oligomers (e.g., oligoesters) that can be used in the synthesis
 539 of PUR or unsaturated polyester resins (UPR) [95,96].

540 PA6, a polymer formed by ring-opening polymerization of ϵ -caprolactam, can be depolymerized by hydrolysis
 541 in both sub- and supercritical water conditions to yield ϵ -caprolactam and ϵ -aminocaproic acid [97]. Similarly,
 542 polycarbonates (PC) can be depolymerized to BPA, which can be used to produce PC, as well as epoxy and
 543 polysulfone (PSU) resins [98]. When PUR solvolysis is compared to PET, the former typically produces other
 544 substances that are less suitable for reproducing the original PUR polymer. However, these byproducts can still be
 545 used in the production of lower-grade PUR variants or different types of PURs altogether [99,100]. The main
 546 output of the gasification process is syngas, a combination of hydrogen and carbon monoxide that holds significant
 547 value. This syngas has many applications and can be used to produce a range of products, including methanol.



548
 549 **Fig. 6** Main products (in blue) and other products (in grey) obtained through different chemical recycling
 550 approaches (in yellow) from some typical recyclable plastics (in pink), as well as more valuable products (in green)
 551 obtained from them and the synthesis back to the original or similar polymers with them through solvolysis,
 552 pyrolysis and gasification.

553 3.6 Economic assessment of some chemical recycling options

554 Due to certain differences in technology readiness level, conducting a comprehensive cost analysis for all the
 555 different options in chemical recycling is very challenging. In addition, some quantitative data need to be adjusted
 556 based on reactor configurations, individual company specifics, potential synergies among partners, the nature of
 557 the post-consumer plastic waste streams to be treated, and other factors. For low technology readiness level
 558 technologies for plastic waste recycling, the data available for such an analysis is very scarce. This scarcity is
 559 likely attributed to the early stage of these technologies, where research and development efforts are predominantly
 560 concentrated on refining the technology itself rather than on economic evaluations. Consequently, an exhaustive

561 lifecycle assessment of these emerging technologies falls outside the scope of this article. However, we present
 562 here the economic analysis of high-temperature chemical recycling, namely pyrolysis and gasification, due to their
 563 high technology readiness level and extensive industrial experience with these technologies. Economic
 564 assessments, based on data available in the literature, are summarized in **Table 5** for both pyrolysis and gasification
 565 of PSW in different configurations. Four major economic indicators are reported, including net present value
 566 (NPV), return on investment (ROI), internal rate of return (IRR), and payback period (PP). Therefore, NPV usually
 567 depends on the selling price of the products and the electricity sales associated with the industrial-scale waste
 568 plastic treatment facility. In addition, plastic recycling requires many workers for the process of plastic separation,
 569 which could increase labor costs [78,101]. In general, if the NPV is negative, it indicates that the project is not
 570 economically feasible.

571 **Table 5.** The summary of studies for economic assessment of chemical recycling.

| Technique | NPV | ROI (%) | IRR (%) | PT (Year) | Ref. |
|-------------------------------------|--------------|-----------|---------|-----------|-------|
| Plasma gasification | \$ 3 M | 32.1 | 27 | 5.3 | [102] |
| Pyrolysis | - | 14.2~29.5 | - | - | [103] |
| Pyrolysis | \$ -18~28 M | - | - | - | [101] |
| Upcycling into porous carbon | € 19~48 M | - | 68~152 | - | [104] |
| Gasification | € -160~440 M | - | - | 9~24 | [105] |
| Pyrolysis (naphtha) | € 4.3 M | - | 15.7 | 9.2 | [106] |
| Pyrolysis (naphtha-wax) | € 56.5 M | - | 21.3 | 7.3 | [106] |
| Pyrolysis | € 1.6 M | - | 20 | - | [107] |

572 Notes: NPV (net present value); ROI (return of investment); IRR (Internal rate of return); PT (Payback period); M: millions.

573 There are plenty of factors that influence the profitability of plastic recycling projects. First, the profitability
 574 of chemical recycling is highly dependent on the scale of operation [105]. Compared to smaller scales, large scales
 575 tend to be more economically feasible due to economies of scale [108]. For example, the NPVs of pyrolysis were
 576 estimated at different scales (30, 60, and 100 tons of plastic waste per day respectively). The results showed that
 577 the NPV can be significantly improved by processing larger amounts of PSW, from -6.3 to 28.6 million US dollars
 578 (USD) [101,108]. Secondly, the inclusion or exclusion of feedstock costs will directly affect the profitability of
 579 chemical recycling projects. In most cases, the feedstock for chemical recycling is derived from municipal or
 580 industrial solid waste. Therefore, some pyrolysis plants do not have to pay for the costs of feedstock procuring,
 581 and may even receive additional revenue from waste disposal fees. However, on the contrary, due to the
 582 competitive use of plastic waste, some pyrolysis plants need to pay for feedstock procurement, which could turn
 583 the NPV defective even under the large scale of operation (-18.1, -8.6, -3.3 million USD at three scales: 30, 60,
 584 and 100 tons per day) [102]. Third, the price of the final product(s) will affect the profitability of chemical recycling
 585 technologies. Chemical recycling can convert plastic waste into a range of energy products. Therefore, as the price
 586 of the product increases, the profitability of the plastic-to-energy project may also increase. Instead of producing
 587 only naphtha, the co-production of naphtha and waxes from the pyrolysis of plastic waste can become more
 588 lucrative (NPV increases from 4.3 M€ to 56.5 M€) due to the rising price of waxes [106]. Similarly, Riedewald *et*
 589 *al.* [107] (2021) estimate that if the price of pyrolysis oil increases from € 210/t to € 227/t, the IRR of a pyrolysis
 590 plant can simultaneously increase from 20% to 37%. Thus, high oil prices can stimulate the plastic-to-energy
 591 business model. Finally, chemical recycling will become dependent on carbon-trading mechanisms. In general, the
 592 greenhouse gases emissions from chemical recycling are significantly lower than those from conventional

593 incineration [105]. In addition, the greenhouse gases emissions from chemical recycling can be further reduced by
594 integrating CO₂ capture technology, converting it to porous carbon material [103]. Therefore, by introducing a
595 carbon trading mechanism and by rewarding carbon credits or imposing a carbon tax, chemical recycling can be
596 beneficial for achieving carbon mitigation and neutrality goals in the long term.

597 There are still many deficiencies in the economic assessment of plastic chemical recycling. Although
598 significant progress has been made in validating the technical feasibility, environmental impact, and economic
599 viability of the other stages, comparatively little economic assessment work has been done to evaluate the recovery
600 and preparation activities [109] This is limited by the number of ongoing commercial projects, resulting in
601 insufficient information for comparison [91]. Nonetheless, this does not diminish the potential impact of
602 chemically recycled plastics on the economy and society. In the United States and Canada alone, integrating
603 recycled plastics could address a \$120 billion market, yet they currently meet only about 6% of the demand. This
604 figure only includes plastics re-entering the value chain through technologies like depolymerization or solvolysis,
605 not other outputs from thermochemical processes such as syngas, liquid fuels, or refined oils for high-value
606 chemicals [110].

607 Following this, the enhancement and expansion of the chemical recycling sectors would be accompanied by a
608 stronger and more effective collection system, leading to a decrease in recycling expenses. According to the
609 European Union, this could result in savings of hundreds of euros per ton of plastic waste collected [111].
610 Additionally, there would be positive impacts on society such as lower CO₂ emissions and reduced reliance on
611 fossil fuels. By increasing the use of feedstocks with more consistent prices, the sustainability of an economy built
612 on circularity would be improved [13].

613 Finally, the environmental impact of plastic waste could be evaluated from the optic of any waste management
614 activity. On the one hand, it renders the service of treating a waste, that otherwise will be disposed in a landfill,
615 and on the other hand, it returns a product or an energy source. Therefore, the assessment is principally focused on
616 the numerous impacts that these two activities generate, both positives and negatives [112–114]. For a complete
617 life-cycle assessment (LCA) of PSW, the framework for comparison must first be established, which requires the
618 definition of the value chain to be analyzed, i.e. the feedstock to be treated (MPW, composites, or rather
619 homogeneous streams of polyolefins, PS, PVC, etc.), the technology selected for valorizing such waste (like
620 pyrolysis, solvolysis, gasification, etc.) and the selected application for the recycled good. For the latter, two
621 scenarios can be distinguished: either recycling goods enter the same value chain, i.e. they are used to produce the
622 same original polymer (closed-loop recycling), or they integrate new value chains, yielding different products
623 (open-loop recycling) [16,112,113,115] In any case, such an analysis would require performing extensive
624 calculations and analysis that are out of the scope of this work. However, interested reader may refer to the existing
625 literature on the subject.

626 **4. Other alternatives to conventional recycling strategies**

627 Despite the numerous advantages that chemical recycling provides to manage plastic solid waste (PSW), it is
628 not presented here as a flawless or unique solution. Many chemical recycling techniques are still evolving,
629 requiring advanced technology and expertise, and may not yet ensure adequate recycling rates to meet the
630 economic demands for their sustainability. This section explores alternative approaches, including biological
631 recycling and the development of biodegradable plastics, which complement or serve as alternatives to

632 conventional methods. Additionally, eco-design is highlighted as a crucial strategy to enhance the recyclability of
633 PSW, potentially improving recycling rates. Finally, a relation and comparative analysis of these approaches is
634 provided to elucidate the role of chemical recycling within the broader context of a circular economy.

635 **4.1 Biological recycling**

636 Two primary biological approaches have been commonly investigated to reduce the environmental impact of
637 plastic waste: (i) the application of specific microorganisms and enzymes for biodegradation of plastic waste and
638 (ii) the development of biodegradable plastics. Microbial and enzymatic degradation of plastic waste is a promising
639 strategy to depolymerize these materials into their monomers for recycling, to convert them into carbon dioxide,
640 water, and new biomass, or to produce high-value products. Enzymes capable of degrading plastics have been
641 isolated from a variety of sources, ranging from marine ecosystems and soil to plastic landfills and invertebrates
642 [116]. A number of enzymes have been identified for the degradation of PE, PS, PP, PVC, PET, and PU [117].
643 The most extensive research among them relates to the development of exceptional PET hydrolytic enzymes for
644 PET biological cycling [118–121]. In 2016, Yoshida et al. reported a novel bacterium, *Ideonella sakaiensis* 201-
645 F6, which efficiently employs PET as the main carbon and energy source for cell growth [118]. PETase isolated
646 from *Ideonella sakaiensis* shows great potential in PET degradation due to its relatively high activity at room
647 temperature compared to the other PET-degrading enzymes [119]. By determining the tertiary structures of PETase
648 and its ligand-bound complexes, Han *et al.* [120] elucidated the molecular mechanism of enzymatic PET
649 hydrolysis. Based on the structural information and biochemical studies of PETase, the variant PETase R280A
650 with improved PET-degrading activity was constructed [121]. Alper *et al.* [122] used a structure-based deep
651 learning algorithm to develop a highly robust and active PET hydrolase that demonstrated superior PET-hydrolytic
652 activity compared to both wild-type and engineered alternatives. This PET hydrolase was able to completely
653 degrade whole, untreated, post-consumer PET from 51 different plastic products within one week and as quickly
654 as 24 hours at 50 °C. Future research may focus on investigating the impact of higher modification ratios on enzyme
655 performance through the implementation of more efficient conjugation methods. Despite significant recent
656 advances in biological recycling technology, there is still room for improvement before achieving commercial
657 viability. Nevertheless, the technology has broad development prospects due to its low energy consumption and
658 environmental friendliness.

659 **4.2 Biodegradable polymers**

660 As another biological approach to reduce the environmental impact of plastic waste, the development of
661 biodegradable plastic materials has gained considerable attention. According to European Bioplastics (EUBP),
662 poly-(butylene adipate-co-terephthalate) (PBAT) and poly (lactic acid) (PLA) have become the two major
663 biodegradable plastics with the highest production capacity in the world, accounting for 4.5 % and 20.7 % of the
664 total bioplastic production capacity (EUBP, 2022) [123]. These biodegradable and bio-based plastics are designed
665 to undergo fragmentation and assimilation by microorganisms, using different conditions according to their unique
666 biodegradation characteristics. This property is advantageous in mitigating the effects of improper disposal in both
667 marine and terrestrial ecosystems, reducing contamination and accumulation of microplastics in the environment
668 [124,125]. Despite some reports claiming that biodegradable plastics may produce more microplastics, a growing
669 body of research suggests that degradation of non-biodegradable plastics may result in the persistence of

670 microplastics [126,127]. While fragments and microplastics derived from inherently biodegradable materials are
671 more likely to undergo further biodegradation and eventual mineralization [124,125,128].

672 However, it is important to note that biodegradable plastics can have limitations. They may have inferior
673 barriers and mechanical properties compared to non-degradable plastic materials [129–131]. Furthermore, their
674 degradation often requires specific environmental conditions, and they may not be suitable for composting. For
675 instance, PLA is biodegradable but is not considered suitable for home composting [131]. In addition, certain
676 biodegradable plastics may not be fully biodegradable in marine ecosystems, highlighting potential complexities
677 in their overall environmental impact. Basically, given the current state of knowledge, it is not yet feasible to
678 switch exclusively to these biodegradable plastics. Nevertheless, these materials have valuable potential in specific
679 areas such as biomedical applications, packaging, and agricultural mulching. Therefore, further research and
680 development are necessary to verify the safety and applicability of biodegradable plastics prior to their widespread
681 use in the natural environment.

682 **4.3 Eco-design**

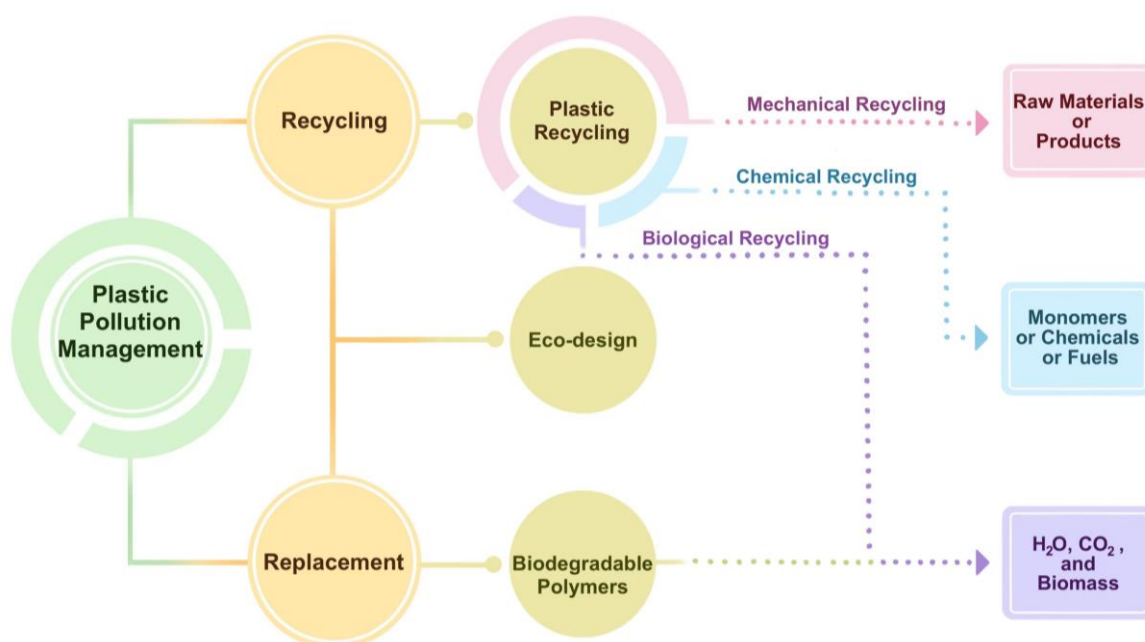
683 Another strategy to place PSW in a circular economy is the eco-design of the original plastic materials. Eco-
684 design can be described as a set of principles aimed at reducing the environmental impact of a given product
685 throughout its life cycle without compromising its properties and functionalities. This proactive approach can be
686 used to minimize the waste associated with materials, improve their recyclability, and overall, reintegrate the
687 resources already in the consumption-production cycle instead of extracting and using new ones [132,133].

688 In this regard, two types of strategies are considered during the conceptual phase of product development,
689 focusing either on the material components or the material itself [132,134]. The former involves designing a
690 product to be durable, reusable, and easily integrated into a new life cycle. In the case of plastics, the choice of
691 bio-based matrices or additives would also reduce the environmental impact, although they are not always
692 biodegradable [134–136]. For example, it is possible to produce bio-based films from biomass instead of fossil
693 resources, which are mainly considered for food packaging. The eco-design of these products involves selecting
694 the appropriate combination of matrices, plasticizers, and other additives, to ensure that the material possesses
695 desirable properties while also being more environmentally friendly [136]. PLA filament for 3D printing
696 applications, hydrogels made from starch, and tablets for drug formulation made from cellulose derivatives, are all
697 examples of this approach [137–139].

698 On the other hand, the design could also focus on improving the recyclability of the product by choosing simple
699 and mono-materials or reusing recycled goods to manufacture new products. In the specific case of PSW, there is
700 currently a technical gap in the redesign of most of the non-mechanically recyclable plastics [134]. This barrier to
701 the circular economy model could be overcome by taking advantage of chemical recycling, whose main strength,
702 as already discussed, is the possibility of treating multi-layer, multi-material plastics. The role of eco-design should
703 then focus on overcoming the technical difficulties of the various chemical recycling technologies. This requires a
704 close relationship between designers and chemical recycling actors. This will lead to an increased flow of PSW
705 suitable for recycling, which is necessary for the profitability of these processes on a large scale, but also to ensure
706 a market for these new products.

707 **4.4 Relationship and comparison among strategies**

708 In summary, biological recycling, biodegradable polymer substitution, and eco-design are all approaches of
709 plastic pollution management. They serve as supplementary or alternative technologies to mechanical recycling
710 and chemical recycling technologies. Biological recycling technology for PSW mainly refers to the use of
711 microorganisms or enzymes to recycle PSW. Biodegradable polymers are an effective way to reduce
712 environmental pollution caused by PSW from the original source, as they serve as alternatives to recycling methods.
713 Eco-design involves the use of recyclable plastics and/or biodegradable plastics and other degradable materials to
714 enhance the recyclability of products from the design stage. The relationship between these three approaches and
715 the mechanical and chemical recycling of PSW is illustrated in **Fig. 7**.



716

717 **Fig. 7** Alternative recycling and replacement methods to conventional recycling strategies.

718 The main characteristics of mechanical, chemical and biological recycling processes are outlined in **Table 6**.
719 In general, mechanical recycling requires a lower level of expertise, energy input, and operating costs, whereas
720 chemical and biological recycling yield a wider range of products with specific applications [140–143]. In terms
721 of environmental assessment, mechanical and biological recycling have been found to be more environmentally
722 beneficial than chemical recycling [144,145]. In addition, it should be noted that mechanical recycling does not
723 result in the production of non-CO₂ greenhouse gases, and biological recycling produces limited amounts of them.
724 However, certain chemical processes, such as pyrolysis, can produce non-CO₂ gases such as methane, ethane, or
725 other hydrocarbons [12]. Conversely, the use of pyrolysis oil, a flagship product of chemical recycling, can reduce
726 the consumption of fossil crude oil for manufacturing virgin plastics, which is not possible with other alternatives
727 [60]. In term of energy consumption, if chemical processes require more energy, it could be recovered for energy
728 generation. For example, steam and process water could be reused to reduce the overall environmental impact
729 [143].

730 **Table 6.** Comparison of the key aspects for mechanical, chemical and biological recycling.

| Parameters | Mechanical recycling | Chemical recycling | Biological recycling | Ref. |
|------------------------------|---|---|---|----------------------|
| General | Well-known technology. Profit-making technique. Low level of expertise demand. Wide Industrial large-scale utilization. | Some processes are well-known while others need further development. Accomplishment of the sustainable development goals. High level of expertise demand. Industrial deployment is moderate but growing. | Need for process development. Mild conditions. No secondary pollution. Could be applied on a large scale. Lack of high-performance degrading bacteria/enzymes. Low yield of large-scale preparation of bacteria/enzymes | [11,116,142,146,147] |
| Input | Limited to monolayer plastics. Requires pre-treatment. | Efficient for diverse wastes: heterogeneous mixtures, or plastic containing halogenated compounds. Needs high quantities to be profitable. Requires pre-treatment, but fewer sorting than mechanical recycling. | Currently not suitable for all types of materials. Pretreatment of wastes to more enzyme-attackable is necessary. | [11,146,148,149] |
| Output | Excellence of products depends on the condition of input. | Specific, but pure value-added products. | Value-added products Others, including microbial biomass, salt, and CO ₂ . | [11,117,146,150] |
| Environmental impacts | Low carbon emissions. No emissions of non-CO ₂ greenhouse gases. | Low carbon emissions: reduce fossil fuel extraction and therefore CO ₂ emissions. Some processes produced methane, ethane, and other hydrocarbons. | Low greenhouse gas emissions. Eventually no harmful gases and deadly compounds released. | [12,145] |
| Energy consumption | Low energy requirement: Most energy is used for mixing, shredding, etc. Energy cannot be retrieved. | High energy requirement: used for thermal degradation, maintaining high temperature and pressure. Energy can be recovered through energy generation of specific products. | Low energy consumption. Energy cannot be retrieved. | [12,151] |

731 Despite the weaknesses and challenges that chemical recycling technologies still have to overcome, it is clear
732 that they offer a recycling solution that other alternatives do not, especially in the context of a circular economy.
733 The authors agree that the best solution to the plastic waste dilemma is first and foremost to reduce the consumption
734 of these materials, as the best recycling is the one that does not need to be performed. Secondly, improving the
735 design of plastic materials would increase the flow of plastic that can be recycled or redirected to existing value
736 chains. However, this will not eliminate the presence of plastic waste, which must be recycled to avoid polluting
737 ecosystems. For those streams of composite materials, unsorted waste, and those with varying degrees of
738 contamination that are difficult to recycle using simpler methods, chemical recycling is the solution for
739 reintroducing them into the circular economy.

740 5. Conclusions and recommendations

741 The changes in national and international policies, such as import and export bans on plastic waste, as well as
742 regulations on quantity and quality control of plastic waste, provide an opportunity to achieve a circular economy.

743 This is an important step towards ending conventional plastic waste management. Chemical recycling is a powerful
744 technique for managing plastic waste. It is a valuable solution to solve the problems of heterogeneity, complex
745 constitution, and contamination that prevent effective and sustainable recycling of these residues through
746 mechanical recycling. They can upcycle plastic wastes into the beginning of new value chains, or into new valuable
747 products by using selective processes such as solvolysis or more flexible solutions like thermochemical
748 conversions. Consequently, the demand for a circular economy has driven the innovation of chemical recycling
749 solutions for plastic waste.

750 Except chemical recycling, biodegradable polymers and design-for-recycling polymers are gaining increasing
751 attention. Are these materials the key to solving the plastic pollution problem? The answer may be “No”.
752 Biodegradable plastics are necessary in certain areas, such as agricultural mulching films, biomedicine, and
753 compostable waste bags, it is still essential to ensure the effectiveness of plastic waste collection and recycling in
754 other applications. This is because even plastics that may degrade rapidly in composting conditions may not readily
755 degrade in natural environments such as seawater or soil, let alone almost all the modifications, additives and
756 blends for the plastics that actually affect their degradability. Therefore, further research is needed to evaluate their
757 environmental behavior and effects. In terms of design-for-recycling, it is neither easy to design polymers with
758 both high recyclability and excellent properties, nor to develop catalysts with high efficiency, selectivity, tolerance,
759 and low cost to overcome the challenges of energy-intensive and unselective, as well as harsh reaction conditions
760 during recycling processes [152]. Therefore, it is difficult to achieve industrialization for designed polymers to
761 date, although most chemical recycling approaches for common commodity plastics are also far from industrial
762 application. Accordingly, a two-pronged strategy for sustainability will be pursued in the near future. In other
763 words, the status of chemical recycling in the field of plastic pollution management is difficult to be replaced by
764 biodegradable polymers and design-for-recycling polymers in a short period of time.

765 Currently, the development levels of different chemical recycling technologies also vary. Some of them, such
766 as pyrolysis, are already implemented on an industrial scale and their global capacity is continuously increasing.
767 While others still need to overcome some technological limitations to become realistic alternatives to be introduced
768 into a circular economy system. Overall, the high cost, high energy consumption, low efficiency, as well as the
769 complicated machinery and technology involved in chemical recycling processes pose barriers to their extensive
770 use. Many factors influence the plastics chemical recycling, and to meet these challenges, some specific scientific
771 research, technological development and policy-making directions and can be explored:

772 Firstly, optimizing the waste collection system by expanding and integrating the collection of various types of
773 waste can be helpful. Future research should focus on advancing waste sorting technologies and smart waste
774 management systems. This includes developing more effective methods for separating different waste, such as
775 textiles, bio-waste, and hazardous household waste, as well as implementing IoT-based solutions for monitoring
776 and optimizing waste collection processes. Enhanced data management tools will also be crucial for tracking waste
777 flows and informing better recycling practices.

778 Secondly, efficient and profitable chemical treatment technologies are required and need to be further developed
779 in the industry. Scientific research should focus on optimizing chemical recycling processes to enhance their
780 efficiency and reduce costs. This includes developing advanced catalysts and improving reaction conditions to
781 increase the yield and purity of recycled materials. Additionally, research should aim at minimizing energy
782 consumption and waste generation during chemical recycling. Matching technology development should

783 emphasize scalable, affordable recycling machinery and incorporate automation and digital advancements to
784 enhance efficiency. Policymakers should consider implementing circular economy models that promote product
785 design for durability, repairability, and recyclability from the outset. This includes encouraging take-back schemes
786 for products at the end of their life.

787 Thirdly, to improve the effectiveness of life cycle assessment (LCA) of plastic chemical recycling, it is crucial
788 to enhance assessment tools, improve data collection, and establish standardized methods. While LCA for chemical
789 recycling has started to take a more holistic view by considering all stages of the product lifecycle, there are still
790 gaps in research that need to be addressed. A comprehensive approach to LCA can provide valuable insights into
791 the sustainability of chemical recycling processes. Efforts should be directed towards improving data collection
792 and reporting standards, particularly in terms of energy consumption, emissions, and by-products, to reduce
793 uncertainties in LCA results. Standardized methodologies for LCA in chemical recycling are essential to ensure
794 consistency and comparability across studies.

795 Fourthly, both developed and developing countries can enhance their ability and standards for sustainable and
796 responsible management of plastic waste. Governments should implement regulations and standards for managing
797 plastic waste. They should create comprehensive technical specifications and standards to ensure the safety,
798 efficiency, and eco-friendliness of chemical recycling processes. These standards should cover areas such as
799 pretreatment of recyclable materials, chemical processing, and quality control of products. Standardizing processes
800 will improve the reliability and consistency of the technology and promote uniformity within the industry.
801 Governments should also establish and enforce effective waste management policies that prioritize reducing,
802 segregating, and recycling plastic waste. These policies could include incentives for recycling facilities,
803 requirements for extended producer responsibility (EPR), and penalties for non-compliance. Additionally, these
804 policies should be customized to address the unique needs and capabilities of different regions, ensuring that both
805 developed and developing countries have the necessary frameworks to manage plastic waste efficiently.

806 Eventually, the demand for recycled plastic should be encouraged by raising consumer awareness about the
807 need and benefits of choosing recycled plastic over virgin plastic. There is a risk of a mismatch between production
808 and consumption due to the higher cost of recycled plastic products, which can be a barrier for the majority of the
809 population. Driving the demand for products containing recycled plastic would stimulate investment in chemical
810 recycling technologies, thereby increasing profitability and production of plastics with high recycling rates.
811 Policymaking should involve creating incentives that make recycled plastic products more affordable and
812 appealing. For example, policies could include subsidies or tax breaks for manufacturers that use recycled materials,
813 which can lower costs for consumers. Additionally, implementing labeling schemes that clearly identify products
814 made from recycled plastics can help consumers make informed choices.

815 **Author contributions**

816 The manuscript was written through the contributions of all authors.

817 **Conflicts of interest**

818 There are no conflicts to declare.

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